

# Capture of high-altitude precipitation by a low-altitude Eocene lake, western U.S.

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## ABSTRACT

Sedimentary facies of the Eocene Green River Formation reflect a rapid increase in water supply to Lake Gosiute ca. 49 Ma, marked by a stratigraphic fill-to-spill surface. Deposits below this surface constitute repetitive lacustrine expansion-desiccation cycles, whereas those above consist of continuous profundal lacustrine mudstone, grading upward into volcanoclastic deltaic sandstone. Above the fill-to-spill surface, calcitic mudstone  $\delta^{18}\text{O}$  decreases from  $\sim+26\text{‰}$  to  $+20\text{‰}$  over an interval representing  $\sim 100$  k.y. We interpret this shift to have resulted from capture of a foreland river (or rivers) that drained higher topography north of Lake Gosiute, most likely in north-central Idaho. Accurate paleoelevation estimates derived from stable isotopic records in intermontane basins thus may require detailed knowledge of regional drainage systems.

**Keywords:** Green River Formation, drainage, lacustrine, carbonate, Laramide, paleoaltimetry.

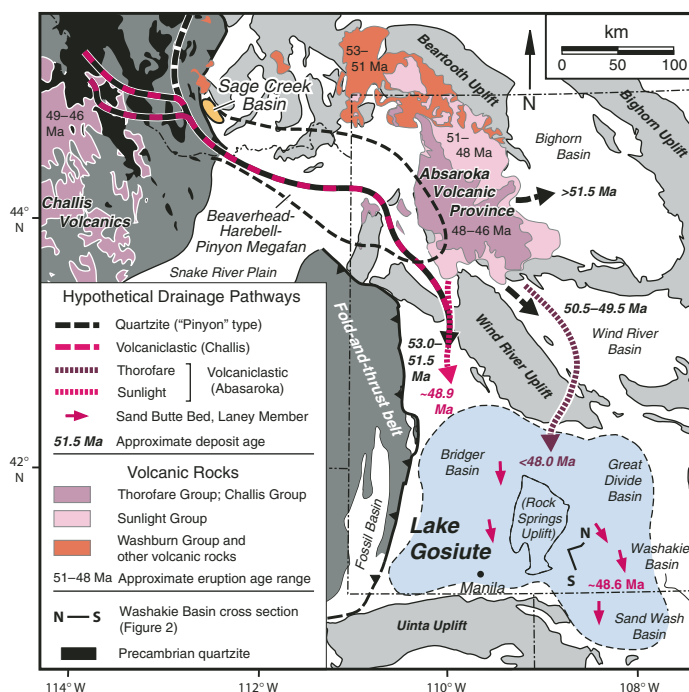
## INTRODUCTION

Numerous studies have used oxygen isotope ratios ( $\delta^{18}\text{O}$ ) in authigenic minerals to infer changes in meteoric water isotopic composition, which may reflect uplift-induced perturbations in atmospheric circulation and isotopic fractionation with increased elevation (e.g., Quade et al., 1989; Chamberlain and Poage, 2000; Poage and Chamberlain, 2001; Rowley et al., 2001). However, foreland rivers commonly carry meteoric water hundreds of kilometers from its point of origin. Rivers fed by precipitation at relatively high elevations may therefore exert a significant influence on the isotopic record of distant foreland lakes at lower elevations.

The Laramide basins of the western U.S. provide an ideal place to test this hypothesis. Carbonate-rich lacustrine deposits of the Green River Formation are widespread in several basins, and span  $\sim 10$  m.y. of the early to middle Eocene. The stratigraphy, geochronology, and drainage relationships between these basins are relatively well documented (e.g., Surdam and Stanley, 1980; Dickinson et al., 1988; Roehler, 1992; Rhodes et al., 2002; Smith et al., 2003, 2008). However, the Eocene elevation of adjacent Laramide uplifts is more controversial; debate is focused on the interpretation of basal  $\delta^{18}\text{O}$  records (Norris et al., 1996, 2000; Dettman and Lohmann, 2000; Morrill and Koch, 2002; Fricke, 2003). This study is the first to examine the potential influence of drainage not only from basin-bounding uplifts, but also from transport of water from more distant, extrabasinal sources.

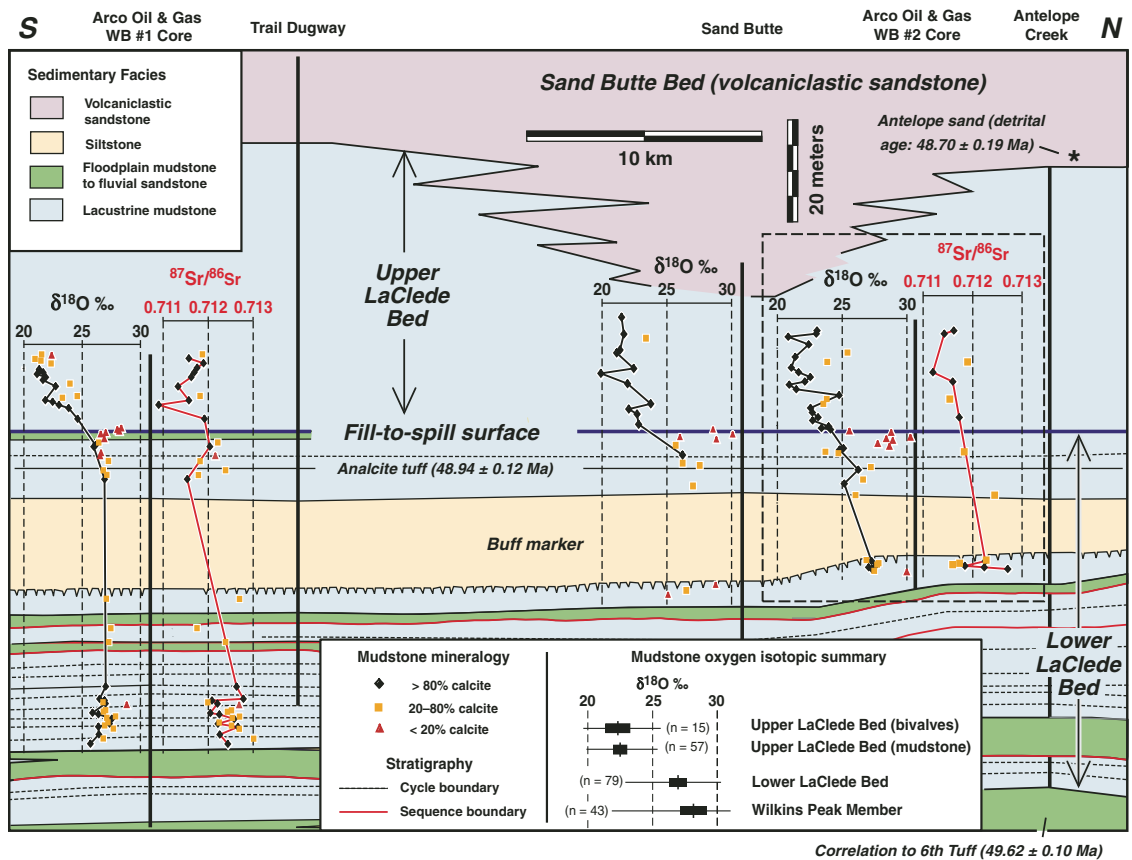
## LAKE GOSIUTE FILL-TO-SPILL SURFACE

The LaClede Bed of the Green River Formation (Roehler, 1992) was deposited across the greater Green River Basin by Eocene Lake Gosiute (Fig. 1). It is dominated by autochthonous lacustrine carbonate facies, with minimal reworked carbonate detritus. The lower LaClede Bed is characterized by 1–5-m-thick facies successions recording repeated expansion and desiccation of Lake Gosiute (Surdam and Stanley, 1979; Fig. 2). These cycles commonly include a basal algal stromatolite or other shallow



**Figure 1.** Location and inferred drainage pathways into northern Laramide basins during the Eocene. Hypothetical drainage pathways are based on paleocurrent measurements and clast types (quartzite versus volcanic), delimited by age of enclosing strata (compiled from Krause, 1985; Janecke et al., 2000; Sears and Ryan, 2003; Smith et al., 2008). Arrows in Lake Gosiute indicate progradation of volcanoclastic deltas during Laney Member deposition (Surdam and Stanley, 1980). Challis and Absaroka eruptive ages are recalculated to  $^{40}\text{Ar}/^{39}\text{Ar}$  standard intercalibration values of Renne et al. (1998). Geochronology of Eocene deposits is based on Smith et al. (2008; for additional references, see footnote 1).

**Figure 2. Stratigraphic cross section and isotopic data, Laney Member, western Washakie Basin (see Fig. 1 for location). Geochronology is from Smith et al. (2003, 2008). Inset summarizes range (horizontal line), mean (vertical line), and  $\pm 1$  standard deviation (black bars) of  $\delta^{18}\text{O}$  (‰) for all Wilkins Peak and Laney Member mudstone samples. Mineralogy determined using relative areas of dominant calcite peaks (all peaks between  $29.3^\circ$  and  $29.9^\circ 2\theta$ ) and dominant dolomite peaks (all peaks between  $30.4^\circ$  and  $31.1^\circ 2\theta$ );  $\% \text{calcite} = \frac{\Sigma \text{area}_{\text{calcite}}}{(\Sigma \text{area}_{\text{calcite}} + \Sigma \text{area}_{\text{dolomite}})}$ . Stable isotopic analyses were performed at Stable Isotope Biogeochemistry Laboratory at Stanford University, and reported relative to Vienna standard mean ocean water (VSMOW). Precision of analyses is  $\sim 0.2\text{‰}$ , based on repeated analyses of standards (see Kent-Corson et al., 2006, for a complete description of oxygen isotopic methods). Additional experiments performed on organic-rich mudstone samples before and after removal of organic matter with  $\text{H}_2\text{O}_2$  showed no significant effect of organic matter on  $\delta^{18}\text{O}$ . See Rhodes et al. (2002) for strontium isotopic methods, and the Data Repository for data table (see footnote 1).**



lacustrine facies, then grade upward into laminated, organic-rich dolomitic or calcitic mudstone, representing profundal deposition. Dolomite and mudcracks increase near the tops of cycles, sometimes in association with evaporite minerals or mineral casts. There are 10–11 cycles below an  $\sim 10$  m dolomitic siltstone bed named the “buff marker” by Roehler (1992; Rhodes et al., 2007). Two to three additional stromatolite-bearing cycles are present above the buff marker.

A conformable, regionally mappable fill-to-spill surface separates the lower and upper LaCledde beds, and marks a permanent increase in average net water supply to Lake Gosiute. Strata above this surface record a lake that was continuously filled to its sill level, and likely continuously overflowed. Lake expansion-contraction cycles, mudcracks, and evaporite minerals are absent. Facies consist primarily of laminated to massive organic-rich calcitic mudstone that contains freshwater molluscs. The upper LaCledde Bed grades laterally and upward into dolomitic siltstone and volcaniclastic siltstone and sandstone facies of the Sand Butte Bed. Volcaniclastic deltas progressively filled the Bridger through Washakie Basins from northwest to southeast before spilling into the Piceance Creek Basin to the south (Surdam and Stanley, 1980; Smith et al., 2008).

#### LACUSTRINE CARBONATE $\delta^{18}\text{O}$ AND $^{87}\text{Sr}/^{86}\text{Sr}$

Lower LaCledde Bed samples have an average  $\delta^{18}\text{O}$  of  $+27.0\text{‰}$  overall, and  $+26.3\text{‰}$  in calcite-dominated mudstone. Both  $\delta^{18}\text{O}$  and  $^{87}\text{Sr}/^{86}\text{Sr}$  vary within lake cycles (Rhodes et al., 2002; Fig. 2), but neither shows any clear longer-term trend within the lower LaCledde Bed. Upper LaCledde Bed  $\delta^{18}\text{O}$  decreases rapidly upward for  $\sim 15$  m above the fill-to-spill surface, reaching a minimum that is  $6.4\text{‰}$  less than the average in the lower LaCledde Bed (Fig. 2).  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios decrease from an aver-

age of  $0.712296 \pm 0.000400$  in the lower LaCledde Bed, to an average of  $0.711638 \pm 0.000274$  in the upper LaCledde Bed. A t-test performed at the 95% confidence level shows that these are statistically distinguishable populations. Based on net overall accumulation rates for the LaCledde Bed (Smith et al., 2003, 2008), the  $\delta^{18}\text{O}$  isotopic shift occurred over  $\sim 100$ – $200$  k.y.

#### DISCUSSION

Several lines of evidence indicate that the decrease in  $\delta^{18}\text{O}$  recorded within the LaCledde Bed reflects a change in the composition of Lake Gosiute, rather than an artifact of later diagenesis. Textural evidence for mudstone alteration is absent, and  $100\text{-}\mu\text{m}$ -scale primary lamination is commonly preserved. Similar  $\delta^{18}\text{O}$  and  $^{87}\text{Sr}/^{86}\text{Sr}$  records occur at locations at least 32 km apart, and lower LaCledde Bed cycles preserve large variations in  $^{87}\text{Sr}/^{86}\text{Sr}$  that are directly related to decimeter- to meter-scale facies patterns (Rhodes et al., 2002; Fig. 2). Upper LaCledde Bed mudstone  $\delta^{18}\text{O}$  is nearly identical to that in aragonitic unionid bivalves collected from equivalent rocks north of Manila, Utah (Morrill and Koch, 2002; C. Morrill, 2006, personal commun.; Figs. 1 and 2). Molluscs are absent in the lower LaCledde Bed, but alteration would generally be expected to produce lower  $\delta^{18}\text{O}$  (cf. Morrill and Koch, 2002; Fricke, 2003), in conflict with the relatively high measured values.

One possible explanation for the decrease in Lake Gosiute  $\delta^{18}\text{O}$  is a change in the source of regional air masses that produced precipitation, although there is no direct evidence for this. Alternatively, regional climate could have shifted toward wetter conditions. A  $-5\text{‰}$  change in the lake would require an  $\sim 4\times$  increase in precipitation (cf. Rozanski et al., 1993), an  $\sim 50\%$  decrease in evaporation (based on our mass balance

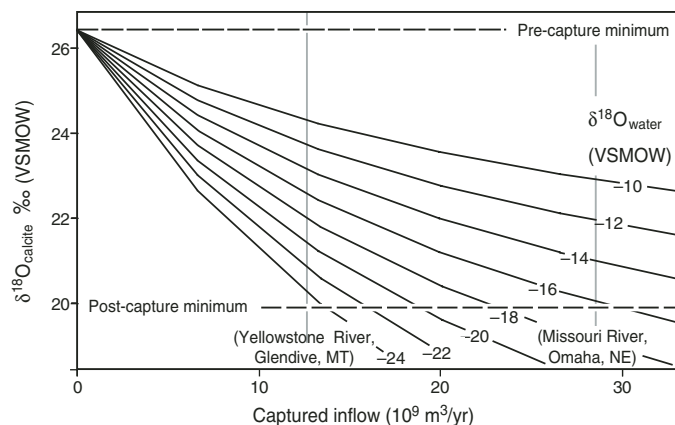
modeling; see following), or some combination of these factors. However, paleobotanical analyses of Green River Formation flora indicate no significant change in mean annual precipitation between deposition of the Little Mountain flora (ca. 50 Ma, Wyoming) and the Bonanza flora (ca. 47 Ma, Utah), although these studies do suggest that mean annual temperatures decreased 4–5 °C (Wing and Greenwood, 1993; Wilf et al., 1998; Wilf, 2000). Atmospheric processes do not fractionate Sr, although changes in  $^{87}\text{Sr}/^{86}\text{Sr}$  could be related to climatically induced spillage from upstream basins into Lake Gosiute (Rhodes et al., 2002). However, recent  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of Green River Formation tuffs demonstrates that the apparent shift toward wetter conditions recorded by the LaClède Bed coincided with an opposite shift, toward long-term evaporative conditions represented by the Mahogany zone, in the nearby Uinta Basin (Smith et al., 2008). It is very unlikely that regional climate change produced both of these facies shifts simultaneously.

An alternative and more plausible hypothesis is that Lake Gosiute captured a river with relatively low  $\delta^{18}\text{O}$  water. To further evaluate we constructed a mass balance using paleobotanical climate values of the Little Mountain flora (for model details see the Appendix in the GSA Data Repository<sup>1</sup>). In the initial model condition, Lake Gosiute exactly fills its basin, with runoff and lake surface precipitation balanced by evaporation. Drainage area was estimated based on modern drainage divides and Eocene paleocurrent data (Smith et al., 2008). The isotopic compositions of lake water and precipitation were calculated from the average calcitic mudstone  $\delta^{18}\text{O}$  in the lower LaClède Bed, based on fractionation during calcite precipitation (O'Neil et al., 1969). The initial model was modified by capture of extrabasinal rivers with varying inflow rates and  $\delta^{18}\text{O}$ , with new inflows exactly balanced by outflow. Lake surface area and depth remained unchanged. Post-capture lake water composition was determined from the minimum calcitic mudstone  $\delta^{18}\text{O}$  in the upper LaClède Bed (Fig. 3). An example of a modern river that could account for the measured change in lake water  $\delta^{18}\text{O}$  is the Columbia River below Priest Rapids dam, where annual discharge is  $106 \times 10^9 \text{ m}^3/\text{yr}$  and  $\delta^{18}\text{O}$  is  $-16.5\text{‰}$  to  $-18\text{‰}$  (Kendall and Coplen, 2001). Lower  $\delta^{18}\text{O}$  values in the river captured by Lake Gosiute may indicate a source area 2 km or more higher than the uplifts surrounding the lake (cf. Chamberlain and Poage, 2000; Rowley et al., 2001), but the possibility of a different air mass composition in the source area cannot be excluded.

The  $\delta^{18}\text{O}$  shift in Lake Gosiute coincided with increased deposition of volcanoclastic sediments and an  $\sim 3\times$  increase in net sediment accumulation rates (Smith et al., 2008). This detritus could have been derived from either the Absaroka or Challis volcanic provinces, but the latter appears more probable due to the occurrence of a similarly abrupt  $\delta^{18}\text{O}$  shift in the Sage Creek Basin in southwest Montana (Fig. 1). Kent-Corson et al. (2006) reported a  $\delta^{18}\text{O}$  shift from  $+20\text{‰}$  to  $+12\text{‰}$  in calcite cement from fluvial volcanoclastic sandstone, dated as between 50 and 47 Ma for this same area. The larger magnitude and lower  $\delta^{18}\text{O}$  values of the shift in the Sage Creek Basin compared to the LaClède Bed are consistent with progressive downstream evaporation (especially from the lake surface) and addition of tributary streams. We propose that both records are related to a common upstream drainage reorganization that occurred in north-central Idaho.

Quartzite-bearing conglomerate units demonstrate a long history of rivers that flowed eastward from north-central Idaho, supporting our hypothesis (Fig. 1; Krause, 1985; Janecke et al., 2000; Sears and Ryan, 2003). Field evidence for eastward drainage continued through ca. 49 Ma, when paleovalleys in eastern Idaho and southwest Montana were filled with Challis volcanic rocks (Janecke et al., 2000; Fig. 1). Mapped geo-

<sup>1</sup>GSA Data Repository item 2008204, Appendix (isotopic data, mass balance model, model explanation, additional references, and Figure DR1), is available online at [www.geosociety.org/pubs/ft2008.htm](http://www.geosociety.org/pubs/ft2008.htm), or on request from [editing@geosociety.org](mailto:editing@geosociety.org) or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.



**Figure 3.** Mass-balance model of the effects of river capture on Lake Gosiute  $\delta^{18}\text{O}$  (‰). Vertical axis shows measured  $\delta^{18}\text{O}$  of LaClède Bed mudstone; upper dashed line indicates average values in lower LaClède Bed, lower dashed line indicates minimum values in upper LaClède Bed. Horizontal axis indicates inflow rate of hypothetical river captured by Lake Gosiute; Yellowstone (MT—Montana) and Missouri (NE—Nebraska) Rivers are shown as illustrative examples (vertical gray lines). Curves represent mixing lines between Lake Gosiute and captured rivers of varying  $\delta^{18}\text{O}$  (labeled on curves), plotted as captured inflow versus resultant mudstone  $\delta^{18}\text{O}$  (see text and Data Repository [footnote 1] for further details). VSMOW—Vienna standard mean ocean water.

logic relationships do not appear to support high relief in the Challis volcanic field ca. 49 Ma (cf. M'Gonigle and Dalrymple, 1996; Janecke et al., 1999), but higher elevations may have existed to the north. The  $^{87}\text{Sr}/^{86}\text{Sr}$  record of the LaClède Bed also appears to be consistent with headwaters in north-central Idaho. Decreased  $^{87}\text{Sr}/^{86}\text{Sr}$  in the upper LaClède Bed likely reflects increased drainage from Eocene volcanic rocks (either the Challis or Absaroka provinces; Norman and Leeman, 1989; Rhodes et al., 2002), but  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios are more variable than accompanying  $\delta^{18}\text{O}$  values. Precambrian rocks are widespread in north-central to northern Idaho and are radiogenic, as are some younger plutons that intrude them (Criss and Fleck, 1987). The  $^{87}\text{Sr}/^{86}\text{Sr}$  measured in the LaClède Bed may thus reflect admixture of relatively radiogenic, high-elevation headwaters with less-radiogenic drainage from lower elevation Eocene volcanic rocks.

## CONCLUSIONS

The results of this study demonstrate that large shifts in  $\delta^{18}\text{O}$  in authigenic mineral phases can occur without any clear evidence for regional climate change. The shift in Lake Gosiute isotopic composition is also too rapid ( $\sim 100 \text{ k.y.}$ ) to have resulted from uplift. This study may support the inference that Laramide ranges had relatively low relief in the Eocene (cf. Fricke, 2003), at least compared to north-central Idaho. The drainage capture hypothesis suggests a ready test, based on inferred spillover of Lake Gosiute into downstream Lake Uinta (Surdam and Stanley, 1980). Related shifts in  $\delta^{18}\text{O}$  or  $^{87}\text{Sr}/^{86}\text{Sr}$  should be found within the time-equivalent Mahogany zone of the Piceance Creek and Uinta Basins (cf. Smith et al., 2008), although the former may be muted due to progressive downstream evaporation.

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